# Progress and Challenges in Specifying Geomagnetic Activity for the Electrical Power Grid

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Space Weather Workshop
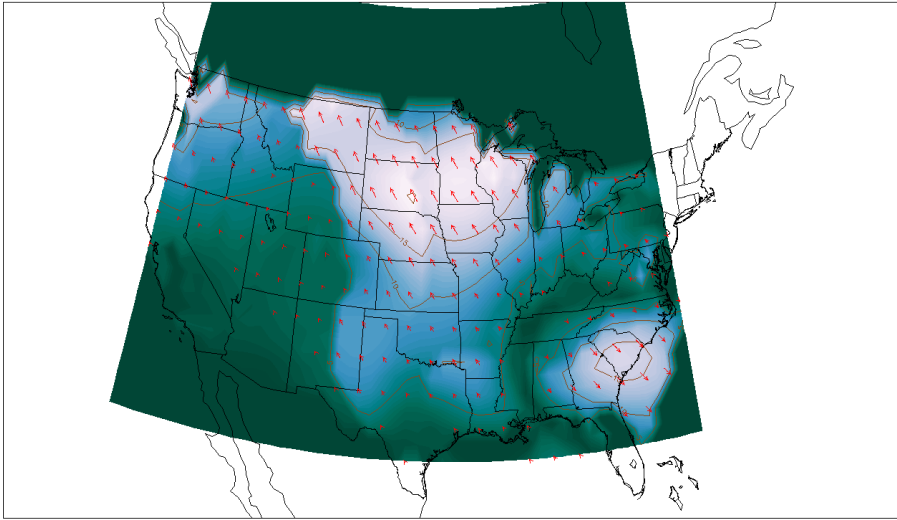08-11 April 2014
Boulder, CO

Outline

- Long-term objective
- Drivers versus response functions
- Normalizing out the response
- The way forward

# Long-term Objective



Geoelectric field map        2003-10-29 00:52 UTC

**Operational product to calculate the local geoelectric field (V/km)**

- **Use real-time magnetometer data as the input**
- **Interpolate geomagnetic field variations on a grid between observatories**
- **Calculate Electric field 'locally' using appropriate conductivity models**
- **User applies the electric field to a model for the power grid to calculate geomagnetically induced currents**
- **User assesses system stability and transformer vulnerability**

# Two key components

- **The External Driver (Space Weather)**
  - Time varying currents in the ionosphere and magnetosphere driven by interaction with disturbed solar wind

- **The Geological Conductivity Structure**
  - Naturally induced currents below Earth's surface
  - Significantly modifies impact of Space Wx driver

# Initial Efforts - 1D Conductivity Models
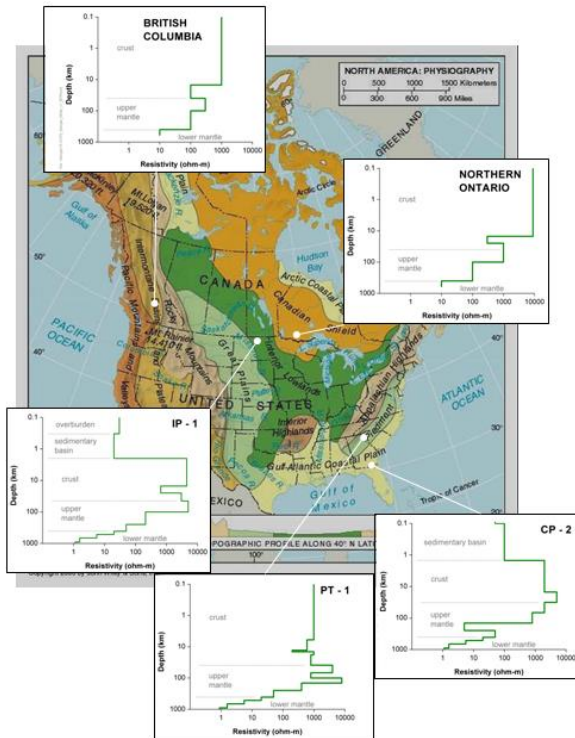


*Credit: Fernberg, Gannon and Bedrosian*



- **1D Conductivity profiles provided by USGS for ~20 different physiographic regions**
- **Preliminary 1-minute values for Ex & Ey have been calculated for 1985-2012**
- **Seven USGS observatories**
- **Overall histograms**
- **Storm Profiles**
- **Climatology conditioned on existing measures (Kp)**
- **Validation work I.P.**
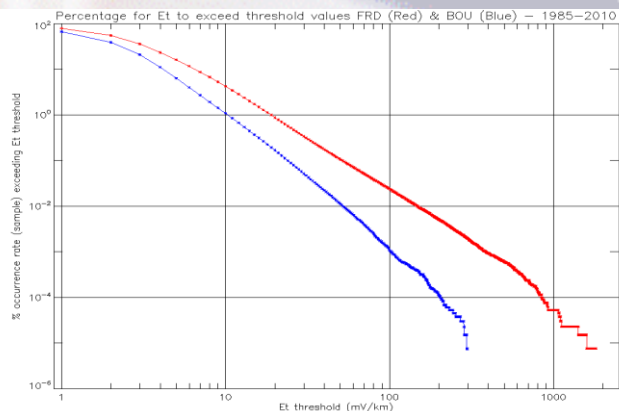
# What about that Conductivity Model?

- **Good News:**
  - Once you figure it out, it won't change
- **Bad News:**
  - It is very complex, inhomogeneous, highly structured, and not always well known
- **Advice of our partners at USGS:**
  - 1D models for the physiographic regions are probably not sufficiently accurate

# Normalized E-field: Uniform Half Space

- **Uniform half-space solution can be used to 'normalize' the geology**

- **Succinctly characterizes the external driving component of the E-field**

- **As specific conductivity models improve, the normalized E-field can be modified fairly easily to incorporate this information**

- **Users may be able to use their own GIC data and system models to empirically determine the 'Earth Transfer function' without knowing the details of the conductivity**

# Uniform half-space

- Conductivity $\sigma_c$, resistivity $\rho_c = 1/\sigma_c$

- Time dependence $e^{i\omega t}$

- Plane wave solution in conducting medium:
  $$E_x = \mathrm{E}_o e^{-k_c z}, \text{where } k_c = \sqrt{i\omega\mu\sigma_c}$$

- Faraday's law: $\quad \boldsymbol{\nabla} \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} = -\mu\dfrac{\partial \boldsymbol{H}}{\partial t}$

- Polarized Plane wave
  $$-k_c \mathrm{E}_x = -i\omega\mu H_y$$

- Hence the electric field is related to the magnetic field by
  $$\mathrm{E}_x = \frac{i\omega\mu}{k_c} H_y$$

- But using the form for $k_c$, above we find
  $$\boxed{\mathrm{E}_x = \sqrt{i\omega\mu\rho_c} H_y}$$

# Uniform Half Space (cont)

- $\sqrt{i\omega\mu\rho_c}$ - 'Earth Transfer Function' for a uniform half-space

- $\omega^{1/2}$ shows the primary dependence of the E-field on $\dfrac{\partial B}{\partial t}$

  - Relatively higher frequencies in B get an extra boost from the earth transfer function
  - Greatest interest is in the 0.001 to 0.01 Hz range

- A normalized value of $\rho_c = 1$ ohm-m can be used to compare the input driver uniformly over the entire continent

- Local calculations have to correct for the effect of the local conductivity – will show the scaling for some simple cases

# Earth Transfer Function: Multi-layer Model

- n layers (i=0,1,2,….,n-1), last layer semi-infinite

- Conductivities $\sigma_i$, depths $h_i$

- $k_i = \sqrt{i\omega\mu\sigma_i}$

- For each layer:

$$E_x = A_i e^{-k_i z} + B_i e^{k_i z}$$

$$H_y = \frac{k_i}{i\mu\omega}\left(A_i e^{-k_i z} - B_i e^{k_i z}\right)$$

- Define impedance $Z_i$ as ratio of $E_x/H_y$ at $z=h_i$

- Derive a recurrence relationship between $Z_i$ and $Z_{i+1}$

- General form:

$$Z_i = \frac{i\omega\mu}{k_{i+1}}\left(\frac{1-\alpha_{i+1}}{1+\alpha_{i+1}}\right)$$

# Multi-layer solution

- Recurrence calculation repeated layer by layer to get the surface impedance:

$$Z_S = \frac{i\omega\mu}{k_0}\left(\frac{1-\alpha_0}{1+\alpha_0}\right) = \sqrt{i\omega\mu\rho_0}\left(\frac{1-\alpha_0}{1+\alpha_0}\right)$$

# Comparison

- Uniform half-space

$$E_x = \sqrt{i\omega\mu\rho_c}H_y$$

- Multi-layer solution:

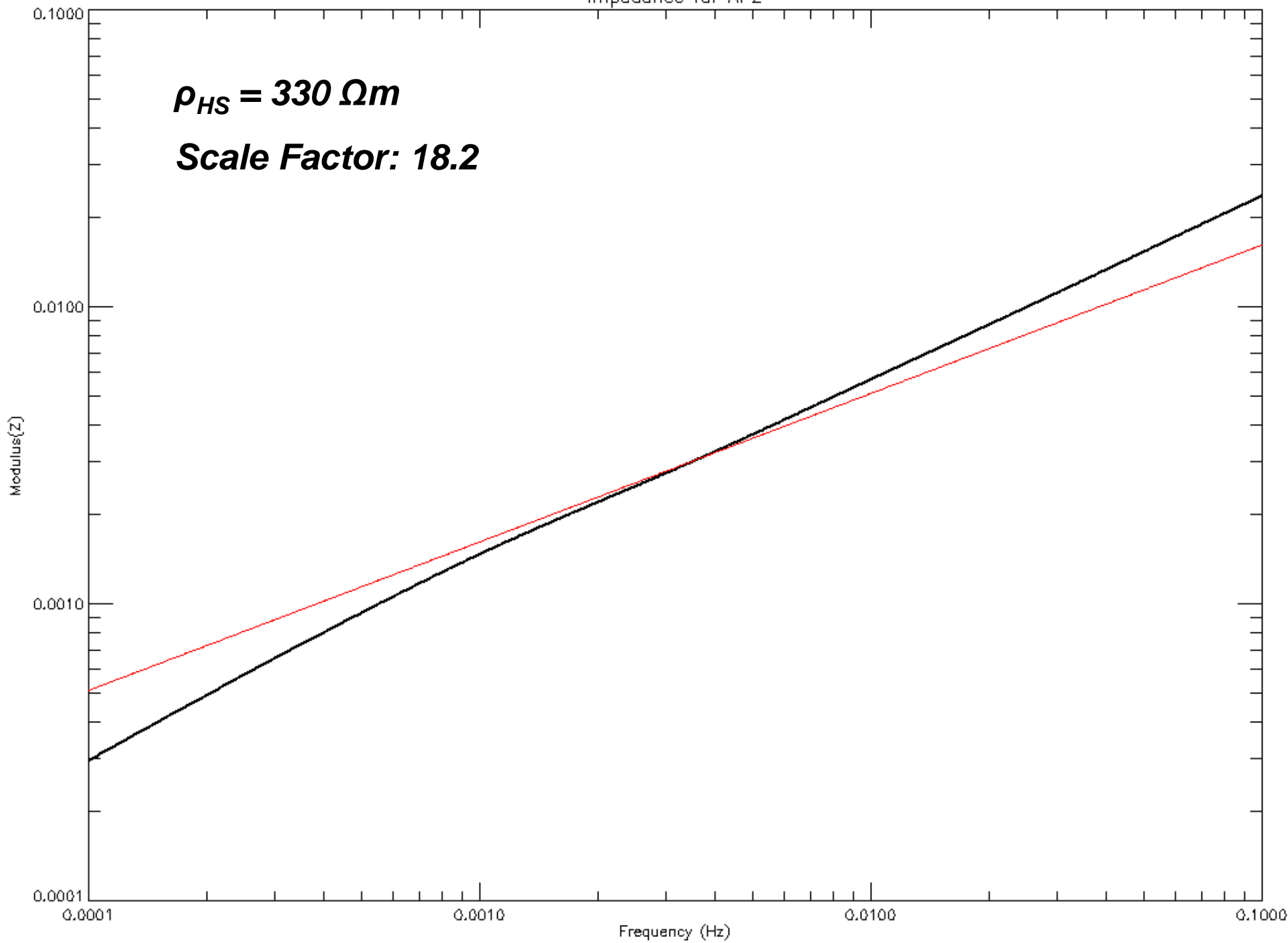$$E_x = \sqrt{i\omega\mu\rho_0}\left(\frac{1-\alpha_0}{1+\alpha_0}\right)H_y$$

- The relationship between the two:

$$E_x(layer) = \sqrt{\frac{\rho_0}{\rho_c}}\left(\frac{1-\alpha_0}{1+\alpha_0}\right)E_x(half\,space)$$

- A comparison of the impedances for uniform half space versus multi-layer solutions can help sort out the relative role of the driver versus the geology
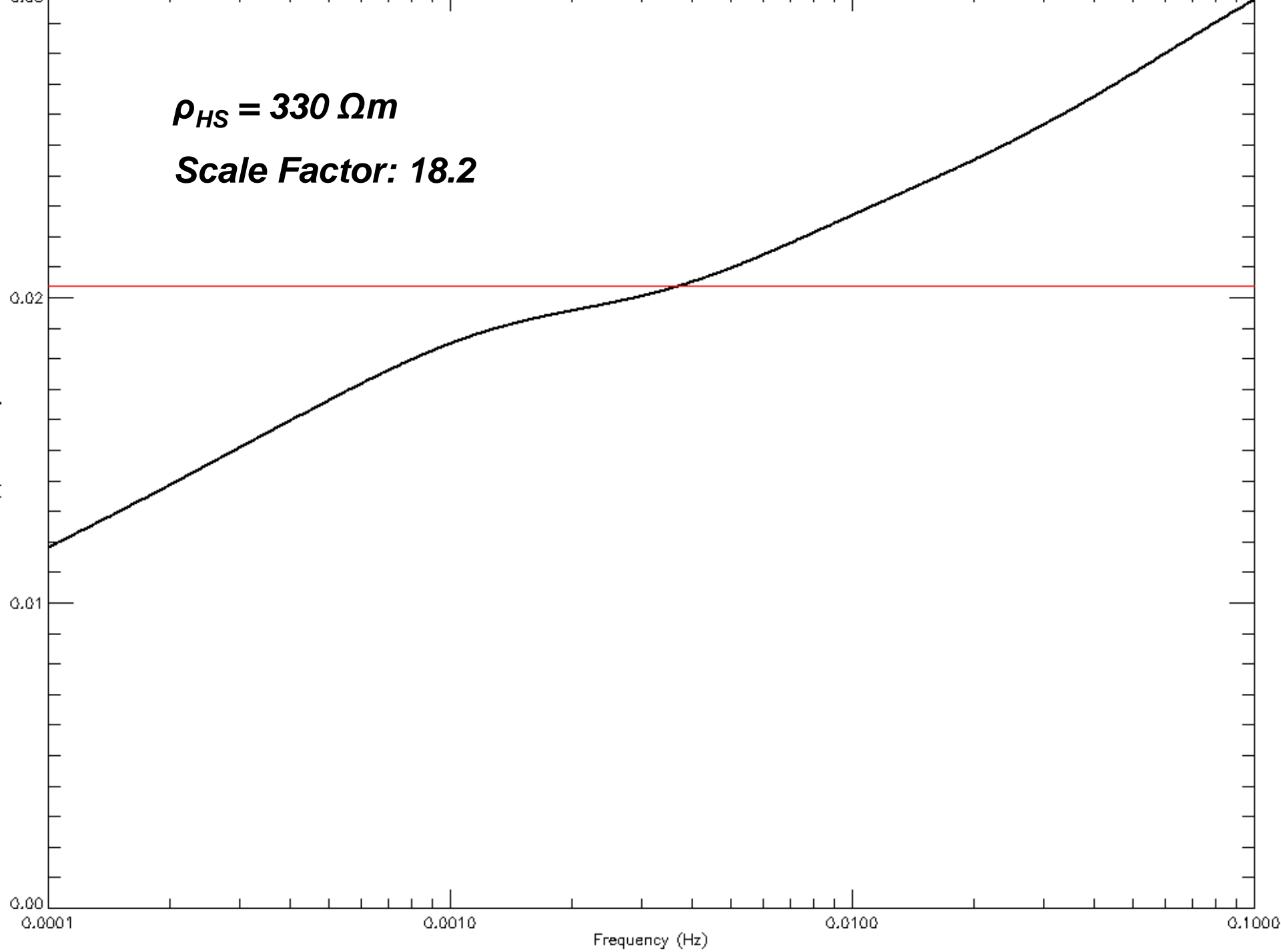
Impedance for AP2

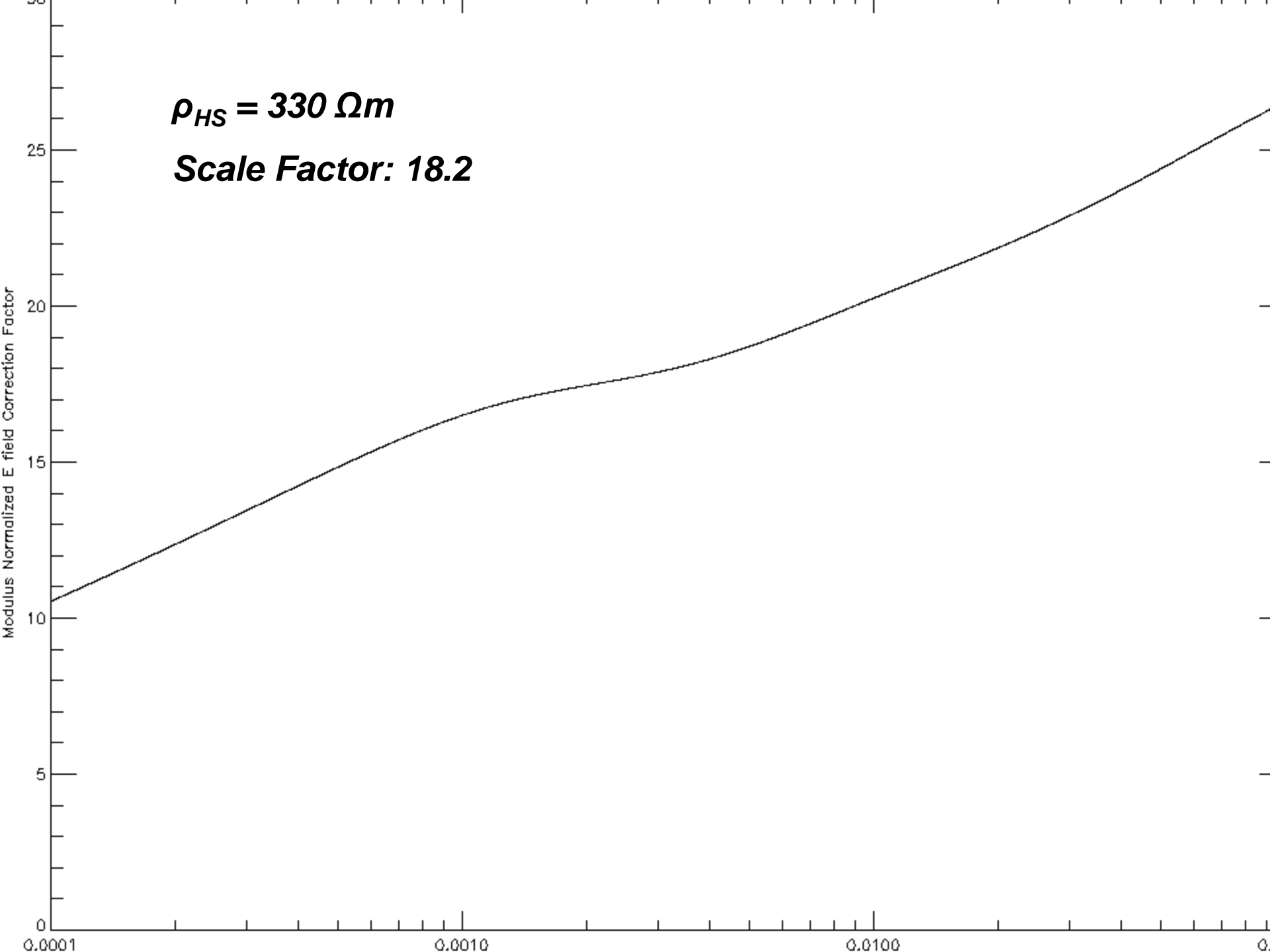$\rho_{HS} = 330\ \Omega m$

Scale Factor: 18.2

$\rho_{HS} = 330\ \Omega m$

Scale Factor: 18.2

Frequency (Hz)

$\rho_{HS} = 330\ \Omega m$

*Scale Factor: 18.2*

# Uniform Half-Space Fitting

| Model | $\rho_{HS}$ (Ωm) | Scaling | Model | $\rho_{HS}$ (Ωm) | Scaling |
|-------|------------------|---------|-------|------------------|---------|
| PT1 | 972 | 31 | IP1 | 179 | 13 |
| CP2min | 676 | 26 | PB1 | 123 | 11 |
| CP2 | 671 | 26 | BC | 98 | 10 |
| OTT | 548 | 23 | AK1A | 87 | 9 |
| CP1 | 491 | 22 | AK1B | 87 | 9 |
| CL1 | 466 | 22 | SL1 | 86 | 9 |
| SU1 | 463 | 21 | CS1 | 44 | 7 |
| IP3 | 463 | 22 | AP1 | 40 | 6 |
| CP2max | 377 | 19 | PB2 | 37 | 6 |
| AP2 | 330 | 18 | CO1 | 36 | 6 |
| NE1 | 314 | 18 | IP4 | 26 | 5 |
| IP2 | 257 | 16 | BR1 | 22 | 5 |

- **Ordered by resistivity, highest to lowest**
- **Scaling factor gives approximate correction to earth-transfer function**
- **The conductivity profile can change the answer by a factor of 6!**

*$\rho_{HS}$ is the resistivity of a uniform half-space that gives the best fit to the multi-layer model over 0.001 to 0.01 Hz*

# The way forward…

- **Working jointly with NOAA, USGS and NRCAN for new operational product development**
- **Validation of the 1D E-field values is in process (NASA/CCMC leading the comparisons)**
  - Looking at accuracy & consistency of techniques
  - Looking for accuracy of the numbers where possible
- **Priority to derive B(r,t) on a spatial grid using existing network with flexibility to expand**
  - **There is a collaborative effort being led by EPRI and DOE to deploy additional magnetometers to improve the accuracy of B(r,t) interpolation**

# The way forward…

- **We are considering providing a 'generic' normalized E(r,t) on a spatial grid using a uniform half space conductivity**

- **There would be an option to provide the corrected calculation from a catalogue of 1D profiles**

- **User requirement for 0.001 to 0.010 Hz is driving the need to obtain higher time-resolution magnetometer data**

  - 1 minute data only goes to 0.008 Hz

  - Analysis needed to assess the error this causes

# Summary

- **Electric grid users need the geoelectric field**
- **The Space Weather part of the calculation is succinctly derived from geomagnetic field data using uniform half-space conductivity model**
- **The conductivity part of the calculation is difficult but significant – options are:**
  - **Use a 1D profile (your own or the USGS physiographic regions)**
  - **Work with the scientific community to improve the conductivity specification in a particular region**
  - **Use GIC data and system models to derive empirical estimates for the earth transfer function**

# Multi-layer solution

- At the bottom of layer i+1:

$$Z_{i+1} = \frac{E_x(h_{i+1})}{H_y(h_{i+1})} = \frac{i\omega\mu}{k_{i+1}} \left( \frac{A_{i+1}e^{-k_{i+1}h_{i+1}} + B_{i+1}e^{k_{i+1}h_{i+1}}}{A_{i+1}e^{-k_{i+1}h_{i+1}} - B_{i+1}e^{k_{i+1}h_{i+1}}} \right)$$

- For notation simplification define:

$$C_{i+1} = \frac{Z_{i+1}}{i\omega\mu}$$

- Then the ratio of B to A for layer i+1 is found to be:

$$R_{i+1} = \frac{B_{i+1}}{A_{i+1}} = - \left( \frac{1 - k_{i+1}C_{i+1}}{1 + k_{i+1}C_{i+1}} \right) e^{-2k_{i+1}h_{i+1}}$$

- At the top of layer i+1:

$$Z_i = \frac{E_x(h_i)}{H_y(h_i)} = \frac{i\omega\mu}{k_{i+1}} \left( \frac{A_{i+1}e^{-k_{i+1}h_i} + B_{i+1}e^{k_{i+1}h_i}}{A_{i+1}e^{-k_{i+1}h_i} - B_{i+1}e^{k_{i+1}h_i}} \right)$$

# Multi-layer solution

- Using the ratio of $B_{i+1}$ to $A_{i+1}$ we get :

$$Z_i = \frac{i\omega\mu}{k_{i+1}} \left( \frac{(1 + k_{i+1}C_{i+1}) - (1 - k_{i+1}C_{i+1})e^{-2k_{i+1}(h_{i+1}-h_i)}}{(1 + k_{i+1}C_{i+1}) + (1 - k_{i+1}C_{i+1})e^{-2k_{i+1}(h_{i+1}-h_i)}} \right)$$

- We can define parameter $\propto_{i+1}$ (using : $d_i$ as the thickness)

$$\propto_{i+1} = \left( \frac{1 - k_{i+1}C_{i+1}}{1 + k_{i+1}C_{i+1}} \right) e^{-2k_{i+1}d_{i+1}} \text{ (note that } d_{N-1} \to \infty, \propto_{N-1} = 0)$$

- Resulting in the recurrence relation:

$$Z_i = \frac{i\omega\mu}{k_{i+1}} \left( \frac{1 - \propto_{i+1}}{1 + \propto_{i+1}} \right)$$

# Multi-layer solution

- Top of semi-infinte layer (bottom of layer N-2):
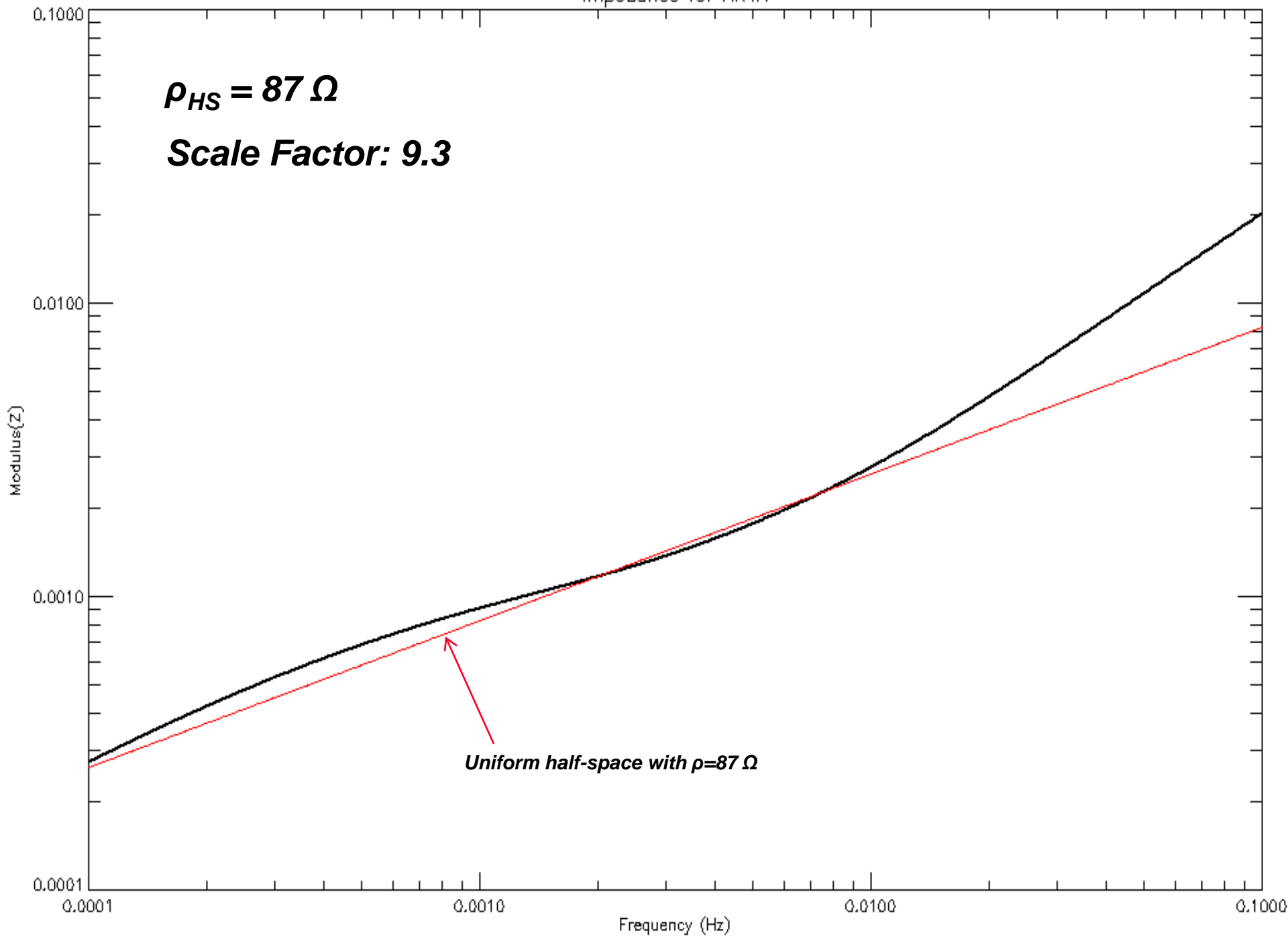$Z_{N-2} = \frac{i\omega\mu}{k_{N-1}}$, thus $C_{N-2} = \frac{Z_{N-2}}{i\omega\mu}$

- Calculate $\propto_{N-2} = \left(\frac{1-k_{N-2}C_{N-2}}{1+k_{N-2}C_{N-2}}\right) e^{-2k_{N-2}d_{N-2}}$

- Find impedance at top of next layer (bottom of layer N-3):
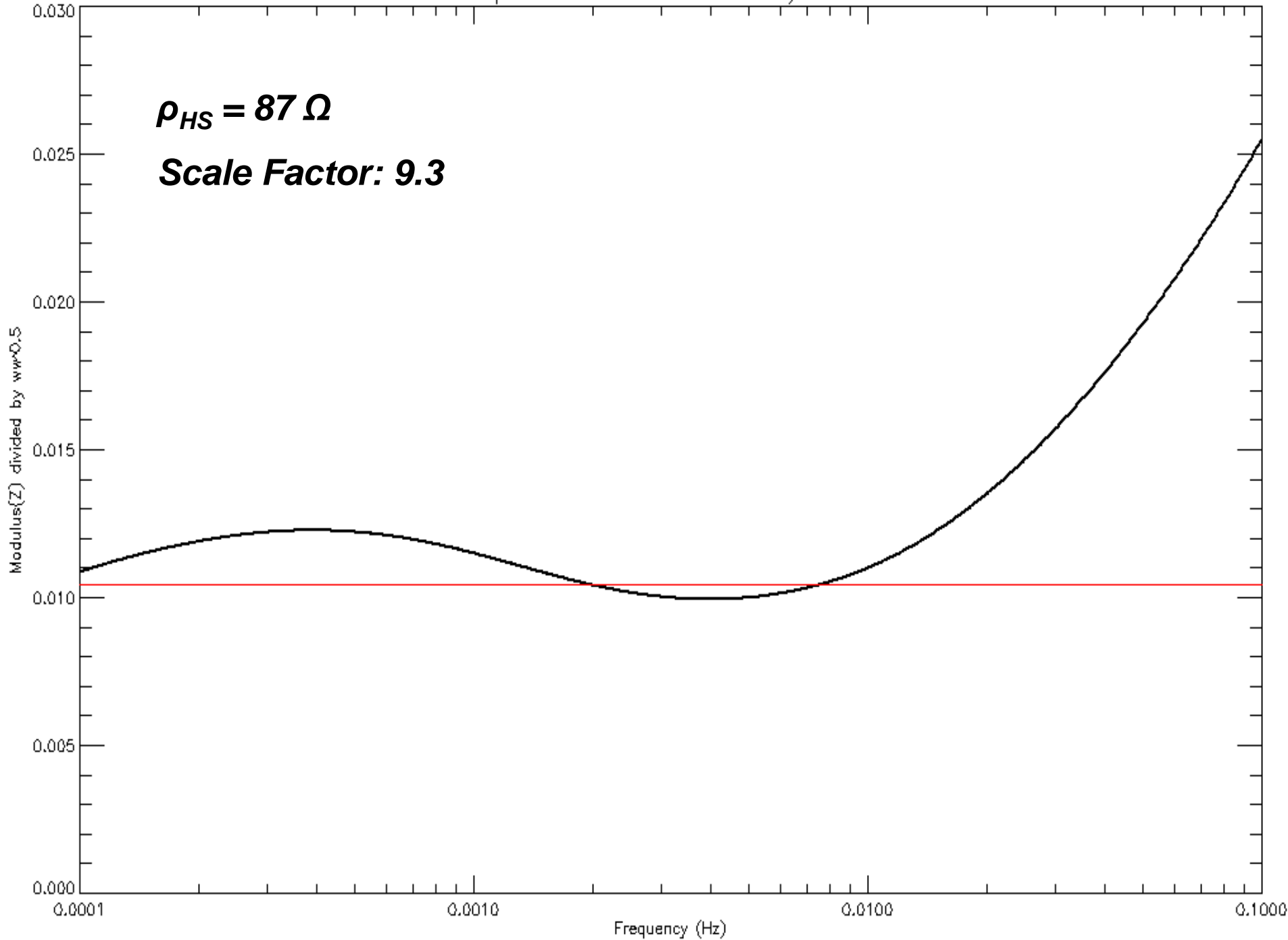$$Z_{N-3} = \frac{i\omega\mu}{k_{N-2}} \left(\frac{1-\propto_{N-2}}{1+\propto_{N-2}}\right)$$

- etc, up to $Z_0$, $\propto_0$. Finally we get the surface impedance:

$$Z_S = \frac{i\omega\mu}{k_0} \left(\frac{1-\propto_0}{1+\propto_0}\right) = \sqrt{i\omega\mu\rho_0} \left(\frac{1-\alpha_0}{1+\alpha_0}\right)$$
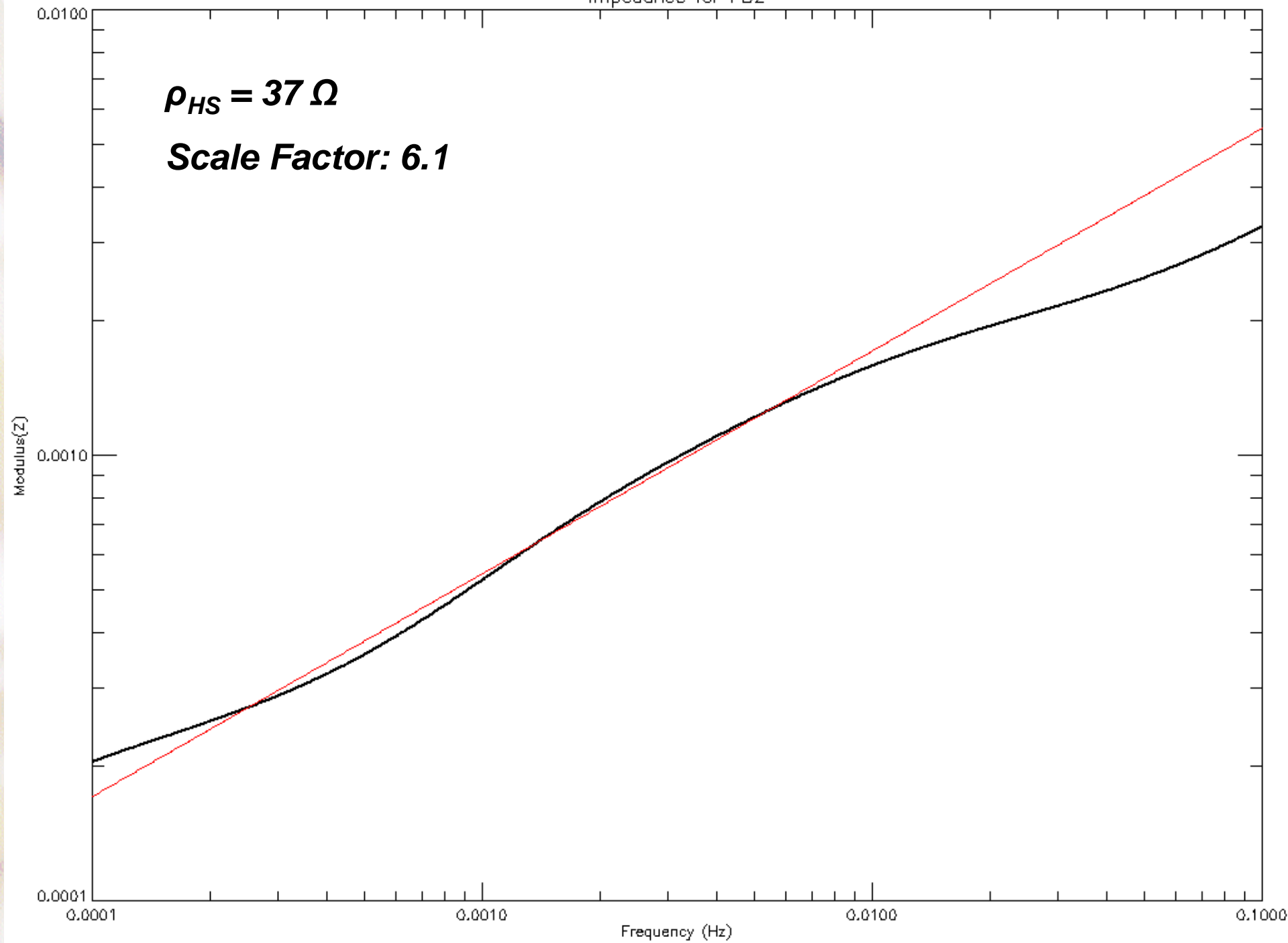
Impedance for AK1A

$\rho_{HS} = 87\,\Omega$

*Scale Factor: 9.3*

*Uniform half-space with ρ=87 Ω*

Modulus(Z)

Frequency (Hz)

Impedance for PB2

$\rho_{HS} = 37\ \Omega$

Scale Factor: 6.1

Modulus(Z)

Frequency (Hz)

Impedance for PB2 normalized by ww^0.5

$\rho_{HS} = 37\ \Omega$

Scale Factor: 6.1

Modulus(Z) divided by ww^0.5

Frequency (Hz)